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Characterizing carbon sequestration in forest products in use

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Abstract

In recent years, much attention has been focused on carbon accounting for harvested wood products in the context of national greenhouse gas inventories. The methods used for national accounting, however, are not suitable for corporate or value chain accounting. This is partly due to the practical difficulties that companies face in assembling the historical production data and other information required by the methods. In addition, national accounting methods yield results that are heavily influenced by historical data and past practices. As a result, these methods provide little insight into opportunities for improvement.

In this paper, a method is described for corporate and value chain accounting of carbon in forest products that avoids many of the difficulties associated with national accounting methods. The method focuses on the long-term effects of current production on future stocks of carbon sequestered in forest products. It estimates the amount of carbon in products expected to remain in use for at least 100 years and, therefore, the method is called the 100-year method.

Data from the U.S. are used to demonstrate the application of the 100-year method. The results indicate that the forest products put into use in the U.S. in 1998 sequestered almost 12 million tonnes of carbon.

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1. Introduction

Almost all of the sequestered carbon in the forest industry value chain is contained in three "pools" – the forest (including above-ground and below-ground biomass), products-in-use, and products disposed in landfills. This paper describes methods for characterizing carbon sequestration in what is perhaps the most often ignored of these three pools – i.e. the pool of carbon in forest products-in-use.

2. An overview of the forest industry value chain

Before examining methods for estimating carbon sequestration, it is helpful to have a general understanding of overall climate profile of the forest products industry.

2.1 Forests

Enormous quantities of atmospheric carbon are stored in forests and forest soils - more than 1,100 gigatonnes (Gt) divided between forest vegetation (approximately 350 Gt) and forest soils (approximately 800 Gt). By comparison, the atmosphere contains about 800 Gt of carbon and the world's oceans contain almost 40,000 Gt [1].

Stocks of carbon in mid- and upper-latitude forests are growing. Stocks of carbon in tropical forests appear to be decreasing, primarily due to deforestation, but there is significant uncertainty in these estimates. Globally, the stocks of forest carbon are thought to be declining, but this will remain uncertain until the estimates for tropical forests are improved [1], [2]. Attempts to develop a global carbon budget suggest that net terrestrial uptake of carbon, including uptake by forests, is in the range of –0.3 to +1.7 Gt/y. This can be compared to global emissions of carbon equal to approximately 6 Gt/y [1], [2].

Although forest carbon stocks are very important to the industry's climate profile, they cannot be viewed in isolation because a sizable fraction of the carbon removed in harvested wood adds to the stocks of carbon stored in products.

2.2 Harvesting and transporting wood to manufacturing facilities

The amounts of greenhouse gases (GHGs) emitted in harvesting and transporting wood to manufacturing operations are primarily determined by the distance traveled and the mode of transportation. Energy data from a U.S.-focused study suggest that GHG emissions from wood harvesting and transport amount to approximately 0.03 tonnes of carbon per tonne of paper [3]. A European-focused study found that total emissions from transport (including raw materials and final products) were approximately 0.02 tonnes of carbon per tonne of paper [4]. The U.S. and European estimates represent perhaps 10 to 20 percent of the manufacturing emissions from the forest products sector. A Canadian study found that wood transportation accounts for nearly 60 percent of the Canadian forest product sector's fossil fuel consumption, a parameter that is highly correlated with GHG emissions [5]. The differences between these studies may be related to the methods used to develop the estimates or to actual differences in transportation distances and other factors.

2.3 *Manufacturing forest products*

The forest products industry relies heavily on carbon-neutral biomass fuels.[2] According to statistics from the Organization for Economic Co-operation and Development (OECD), the forest products industry derives more of its energy from biomass than any other industry [6], [7]. None-the-less, most of the GHGs emitted by forest products industry are associated with the burning of fossil fuels.

Based on information from industry associations and government agencies, it can be estimated that the direct GHG emissions[3] from the pulp and paper industry in Australia, Canada, Japan, the United States, and the European Union (EU) plus Norway and Switzerland amount to approximately 41 million tonnes of carbon [9], [10], [11], [12], [13]. Statistics from the Food and Agriculture Organization of the United Nations (FAO) indicate that these regions produce approximately 63% of the paper and paperboard in the world [14]. This suggests that the GHG emissions from the global pulp, paper and paperboard industry are approximately 65 million metric tonnes of carbon per year.

GHG emissions from wood products manufacturing in OECD countries are approximately 5 million tonnes of carbon per year.[4] FAO statistics indicate that the OECD produces about 70% of the sawn wood and wood panels, suggesting that global GHG emissions from wood products plants are approximately 7 million tonnes of carbon per year [6], [7], [14].

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[2] The term "carbon-neutral" is used to reflect the fact that the carbon in biomass fuels was removed from the atmosphere by photosynthesis and when burned is simply returned to the atmosphere, resulting in no net addition of carbon to the atmosphere.
[3] Direct emissions are from sources owned or controlled by the forest products industry. They do not include emissions associated with purchased electricity, nor do they include CO_2 emissions from biomass combustion (which are reported separately and not totaled with fossil fuel-related CO_2 emissions) [8].
[4] Wood product manufacturing emissions have been estimated from OECD/IEA statistics [6] [7], which exclude fuels used to produce electricity. Unlike pulp, paper, and paperboard mills, however, few wood products facilities produce electrical power from fossil fuels.

In total, therefore, the direct emissions from the forest products industry can be estimated to be approximately 72 million tonnes of carbon per year, which represents just over one percent of global GHG emissions (estimated to be about 6 Gt) [1], [2], [15].

Many forest products manufacturing facilities also purchase electricity. There are no publicly available data, however, that allow the indirect emissions associated with these purchases to be estimated for the global forest products industry. For the pulp and paper industry in Europe, indirect emissions associated with purchased power are approximately 30% less than the industry's direct emissions (estimated from [11] and [16]). In the United States, they are about 40% less than direct emissions [13]. In the wood products sector, indirect emissions often exceed direct emissions, although they are still less than the emissions attributable to electricity purchases by pulp and paper mills (for instance, see [17]).

2.4 Transporting final products to users

The emissions associated with this segment of the value chain are affected by the same factors that influence emissions in transporting raw materials – i.e. transport distance and mode of transport. Like emissions associated with raw material transport, these emissions would be expected to be highly variable.

2.5 Products-in-use

The product use phase of the forest products life cycle is important to the GHG profile of the forest products industry for several reasons. First, emissions are associated with using some forest products. Fossil fuel-derived energy is used, for instance, to heat wood-framed and -sided homes. The differences in energy efficiency between wood-based and other types of homes, and the differences in embodied energy and emissions of the respective building materials (i.e. substitution effects) can be very important to the value chain climate profile.

In addition, this part of the value chain is important because while products are being used, they continue to sequester carbon. This sequestration is an important element of the climate profile of the forest industry value chain. It has been estimated that 40 million tonnes of carbon are sequestered annually in products-in-use [18]. This represents more than one-half of the sector's global direct emissions (estimated above). Carbon sequestration in products-in-use is examined in much great detail later in this paper.

2.6 End-of-life management

After use, most forest products are recycled, landfilled, or burned for energy. This part of the value chain has several effects on the climate profile of the forest products industry.

Perhaps most obviously, when discarded biomass-based forest products are burned for energy they often displace fossil fuels, resulting in avoided GHG emissions.

In addition, used forest products must be collected, a process that requires fossil fuel for transport. Different studies have come to varying conclusions about whether transportation emissions from recovered fiber transport are greater or smaller than those related to wood transport, undoubtedly reflecting, at least in part, differing local circumstances [3][4].

A large fraction of used forest products are recycled, an activity that has multiple and complicated effects on GHG emissions and sequestration along the value chain. Increased recycling may reduce forest harvests and allow longer rotation times, but the benefits to carbon sequestration in the forest are likely to be obscured by the effects of market forces on decisions regarding harvesting and land use. Recycling avoids emissions of methane, a potent greenhouse gas, by keeping used forest products out of municipal solid waste landfills (although increasingly this methane is captured and burned as a biomass fuel, offsetting fossil fuels). Recycling also reduces the amount of carbon sequestered in landfills.

Large amounts of carbon are sequestered in forest products in landfills. In the U.S., for instance, it is estimated that forest products in landfills contain over 1,300 million metric tonnes of carbon and the net additions to these carbon stocks exceed 40 million metric tonnes of carbon per year [19].

To further complicate the analysis of the end-of-life portion of the value chain, in some market segments recycled and virgin fibers compete so that substitution effects within the value chain can become important.

3.0 Options for characterizing carbon sequestration in products-in-use

The products manufactured by the forest products industry contain large amounts of sequestered atmospheric carbon. Worldwide, the industry's annual production (considered equal to total production of paper, paperboard, wood panels and sawn wood) contains approximately 290 million tonnes of carbon [18]. This new production represents additions to existing stocks of carbon in products-in-use. These additions are offset by losses of carbon from the existing stocks as products are removed from service.

Over the last forty years, the net additions to stocks of carbon in products-in-use have varied between 30 and 60 million tonnes of carbon per year. In 2000, these carbon stocks were increasing at a rate of approximately 40 million tonnes of carbon per year

[18]. Due to the long useful lifetimes for many of the industry's products and increased consumption caused by increasing standards of living, stocks of carbon in products-in-use are growing and are expected to continue to grow for the foreseeable future [1], [18].

There are two basic options for estimating changes in the amounts of carbon sequestered in products-in-use. One is to use the methods developed for national accounting of carbon in harvested wood products (HWP). The second is a variation on the national accounting approach that may be better suited to corporate, sector and value chain accounting. Both are explained below.

Before examining the methods, it is important to consider the differences between the issues encountered in preparing national GHG emissions inventories and those associated with corporate, sector, or value chain inventories.

In national accounting one of the most important issues is how to account for the carbon that crosses national boundaries in imports and exports. This is not normally an issue in corporate or value chain accounting because the boundaries for these inventories are usually not set at national borders. Similarly, in national accounting, essentially all forests within the nation's borders are included whereas, in corporate and value chain accounting, it is the forest that provides fiber to the forest products industry that is usually of primary concern.

In national accounting, a very broad definition of "products" is appropriate so the accounting is done on "harvested wood products" or HWP – a term that includes all wood removed from the forest, regardless of its use. In corporate and value chain accounting, a different definition of "product" may be more appropriate because the focus is usually on the valued-added output of the forest products industry.

In addition, national accounting methods are often impractical for use at smaller scales. As explained below, for a company to use them, it must have records of its annual production for many years into the distant past. These data seldom exist, in part because of the numerous corporate mergers, acquisitions, spin-offs and closures that have occurred over time.

For these and other reasons, the approaches used for carbon accounting in national inventories may not be appropriate for corporate, sector, or value chain accounting in the forest products industry. It is important to understand national inventory methods, however, because it is desirable for corporate, sector, and value chain accounting methods to be as consistent as possible with national accounting methods.

3.1 The national inventory method

For national GHG inventories, the Intergovernmental Panel on Climate Change (IPCC) indicates that changes in stocks of carbon in products-in-use can be estimated by several methods. IPCC's Tier 1 method assumes no change in stocks of carbon in products-in-use, but its Tier 2 method estimates stock changes by netting annual additions to stocks in-use against annual losses occurring in the same year [20]. The result is the actual year-to-year change in current stocks of carbon in products-in-use. In this paper, the Tier 2 method is referred to as the "national inventory method."

Using the national inventory method, the change in stocks of carbon is equal to the difference between annual additions to and losses from current stocks of carbon in products in use. Additions to stocks of carbon in products in-use are estimated from annual production and consumption statistics. From these annual additions are subtracted the annual losses from carbon stocks in-use.

A number of methods have been described for estimating annual losses from current stocks of carbon in products-in-use. IPCC's *Good Practice Guidance for Land Use, Land Use Change, and Forestry* suggests that losses from current stocks be estimated by using the following first order decay equation [20] although other relationships can also be used.

Equation 1: Fraction lost per year = Ln(2) / product half-life in years

Because *Equation 1* expresses losses as a fraction of the current pool, one must either measure or mathematically reconstruct the current pool of products-in-use. In IPCC's Tier 2 approach, this is done by starting at a point in the past (the year 1900 is often used) and determining the additions and losses to the product pool year-by-year up to the current time [20]. This requires historic production information and information on how products were used over time. The estimates derived by this method can sometimes be checked against periodic surveys of, for instance, housing inventory.

The Tier 2 national inventory method requires past production and product-use data that cannot be disaggregated down to the individual company level. In addition, because losses from the current pool of carbon are estimated as a fraction of the current pool, the results are heavily influenced by the factors that influence the size of the current pool, i.e. the amounts of past production and time-in-service of past production. The significant influence of past conditions makes national accounting methods unsuited to examining forward-looking opportunities for improvement.

3.2 The 100-year method

An alternative method is available that is better suited to corporate, sector or value chain accounting. Under this alternative, current year additions to stocks of carbon in products-in-use are netted against *future* losses from current year additions.

The result, therefore, is the amount of carbon in the current year's production that is expected to remain in-use for a defined period of time.

In several other applications, IPCC has used 100 years to define similar long-term effects. National inventories submitted under the United Nations Framework Convention on Climate Change (UNFCCC) are prepared using global warming potentials that are derived by "integrating the total radiative forcing of an emissions pulse over a 100-year time horizon…."[1] It has been suggested that a similar approach, involving a 100-year time horizon, could be used to characterize removals via sequestration. The IPCC Special Report on Land Use, Land Use Change, and Forestry, for instance, suggests the following application of a 100-year time horizon in the "ton-year" approach.

> "If the ton-year approach is adopted, incremental credit can be awarded for each year that carbon stocks remain sequestered. The cumulative award of credit would equal the credit from a "permanent" emission reduction of the same magnitude if the stocks remained intact for 100 years. If the stocks were released at any time prior to the 100-year time horizon, only the appropriate amount of partial credit would have been awarded."[1]

Using an analogous approach, a 100-year time horizon can be used to estimate the amount of long-term carbon sequestration that can be expected from newly produced biomass-based products. In this paper, the approach is called "the 100-year method." The 100-year method was first suggested and applied by Dr. Sergio Galeano of Georgia-Pacific Corporation [21]. It is also described in an example of life cycle impact assessment published by the International Standards Organization (ISO) [22].

The 100-year method is conceptually and mathematically simple so it is easy to perform and more likely to be applied consistently from one assessment to the next than the national inventory method. The 100-year method also yields results that reflect conditions and opportunities that are most likely to be influenced by current manufacturers – i.e. those conditions and improvement opportunities that are, or can be, applied to current production.

The primary disadvantage of the 100-year method is that it requires the acceptance of a 100-year time horizon for quantifying long-term sequestration. Other time horizons could, of course, be used but at present it appears that the 100-year horizon is the only one with precedent in the areas of carbon accounting and climate change. This is likely due, at least in part, to (a) the uncertainties associated with projections over longer time periods and (b) an expectation that 100 years will be long enough to develop and deploy permanent solutions for controlling atmospheric CO_2 levels.

4.0 Using the 100-year method

The 100-year method involves four steps.

1. Identify the types and amounts of biomass-based products (e.g. softwood lumber) that are made in the year of interest.
2. Express this annual production in terms of the amount of biomass carbon per year for each product.
3. Divide the final products into categories based on function and allocate the carbon to the functional categories. Some of the functions for softwood lumber, for instance, would be single-family homes, home repair, multifamily residences, shipping containers, and railroad ties.
4. Use decay curves or other time-in-use information to estimate the fraction of the carbon in each functional category, expected to remain in use for 100 years.

5. Multiply the amount of carbon in annual production in products in each functional category by the fraction remaining at 100 years. The result is the amount of sequestered carbon in the products in each functional category attributable to this year's production.

For steps 1 and 2, data on current production is obtained from production records or statistics and the carbon content is estimated by multiplying the production by its carbon content. A common default assumption for paper, paperboard and wood products is that they are 50% carbon by weight (dry) [20]. In general, this is more accurate for wood products than for paper products, which sometimes contain a considerable amount of inorganic material (i.e. filler and coating). Nonetheless, for purposes of estimating stocks of carbon in-use, an assumed carbon content of 50% is probably adequate because only a very small fraction of paper remains in use for 100 years.

Forest products have a variety of uses and a wide range of expected times-in-use. Tissue products are unlikely to remain in use for a year while a significant fraction of the sawn wood used in single family home construction will still be in use in 100 years. Even within a single product type, however, times-in-use can vary substantially. Sawn wood used in shipping containers, for instance, remains in use for a far shorter time than sawn wood used in home construction. It is important, therefore, to understand how forest products are used, not only because product lifetimes vary, but also because time-in-use information is typically associated with specific end use functions. The third step in the process, therefore, is to divide current production into the functional categories for which time-in-use estimates are available.

The time-in-use distributions needed in Step 4 are often represented by mathematical equations that describe decay curves. A key parameter in these equations is usually the product half-life – i.e. the time over which one-half of the original material leaves the pool of products-in-use.

IPCC suggests the use of a simple first order relationship to convert the half-life value into a decay curve that allows one to calculate the fraction remaining as a function of time [20]. The first order decay time-in-use curve is represented by the following equation.

Equation 2: First Order Decay Curve

$$FR = \left(\frac{1}{1 + (0.69315 / HL)} \right)^{Y}$$

Where: *FR = Fraction of carbon remaining in use in year Y*

HL = half-life (years)

Y = elapsed time (years)

Other relationships have been used, however, to convert half-life information into decay curves for time-in-use. The European Forest Institute (EFI) has used the equation shown in *Equation 3* [23].[5]

Equation 3: EFI Decay Curve

$$FR = 1.2 - \left(\frac{1.2}{1 + (5 * e^{-(Y / HL)})} \right)$$

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[5]The equation is slightly different than the version shown in reference [23] so that the result can be shown as a fraction instead of a percentage.

Where: *FR = Fraction of carbon remaining in use in year Y*

HL = half-life (years)

Y = elapsed time (years)

A third option for converting half-life values into decay curves has been used by Row and Phelps and is described by *Equations 4a, 4b, and 4c* [24].[6] The Row and Phelps approach divides the decay curve into three pieces. The Row and Phelps decay curves have been used by the US in preparing its national inventory for UNFCCC.

Equation 4: Row and Phelps Decay Curve

Equation 4a: *If:* $Y < HL/2$

$$FR = 1 - \left(0.4191 * \frac{Y}{HL}\right)$$

Equation 4b: *If:* $Y > HL/2$ *and* $Y < HL$

$$FR = 1 - \left(\frac{0.5}{1 + \left(2 * \ln(HL / Y)\right)}\right)$$

Equation 4c: *If:* $Y > HL$

$$FR = \left(\frac{0.5}{1 + \left(2 * \ln(Y / HL)\right)}\right)$$

[6] The original Row and Phelps 1996 publication [24] contained typographical errors in the equations. The equations shown here have been corrected.

Where: FR = Fraction of carbon remaining in use in year Y

HL = half-life (years)

Y = elapsed time (years)

The effects of selecting different decay curves are illustrated in *Figure 1*. The primary differences occur at times longer than the half-life of the product. This is important because the 100-year method uses only the estimated fraction remaining at 100 years.

Figure 2 shows the results of using the three different decay curves to predict the fraction of the carbon remaining in use at 100 years as a function of product half-life. For products with half-lives of 40 years or less, the Row and Phelps decay curve predicts the largest amount of carbon remaining in use. For products with half-lives between 40 and 100 years, the first order decay curve predicts the largest amount of carbon remaining in use. The EFI model predicts the smallest amount of carbon remaining in use until product half-lives are 80 years or greater, at which point its estimates are close to the Row and Phelps estimates.

Although this discussion has highlighted three decay curves, others are also available [5], [25]. It is not possible to identify one of these as being the most appropriate for all situations. Indeed, it is reasonable to assume that different decay curves will be appropriate under different circumstances. There are several factors, however, that may influence the decision on which curve to select.

First, of the decay curves identified in the literature, only the Row and Phelps decay curve reflects the "archive effect" – i.e. a certain fraction of product is predicted to be stored for 100 years in places such as archives and libraries even though the half-lives are short. As illustrated in *Figure 2*, the first order and EFI decay curves (and others in the literature), fail to incorporate this phenomenon. On the other hand, the first order decay curve is most comparable to the approaches currently described by IPCC in its good practice guidance for national inventories [20]. The importance of these and other considerations will likely vary depending on specific circumstances.

Half-life estimates also vary. It is reasonable to expect some variability between countries due to different building practices, for instance. Some of the differences, however, are probably due to different approaches to estimating product half-life. A summary of much of the available information on half-lives and times-in-use for various forest products is contained in IPCC's *Good Practices Guidance for Land Use, Land Use Change, and Forestry* [20]. The half-life estimates published by Skog and Nicholson in 1998 for the U.S. are summarized in *Table 1* [26].

5.0 Applying the 100-year method to the U.S.

For illustrative purposes, the 100-year method can be applied to the U.S.. There are several souces of U.S. forest products production and consumption data. For this example, data published by the U.S. Forest Service have been used [27], [28].

The 1998 wood products consumption data shown in *Table 2* have been used with the Row and Phelps decay model, the half-life data shown in *Table 1*, and conversion factors explained in *Table 2* to derive an estimate of the carbon in wood products that will remain sequestered in-use for 100 years. The analysis indicates that almost 10 million metric tonnes of carbon, attributable to products put in use in 1998, are expected to remain sequestered in wood products for at least 100 years.

Due to the shorter times in use, the amounts of carbon sequestered in paper and paperboard products are smaller, but still significant. The calculations in *Table 3* indicate that over two million tonnes of carbon are expected to remain sequestered in 1998 paper products for 100 years.

In total, therfore, almost 12 million metric tonnes of carbon, attributable forest products put in use in 1998, were expected to remain sequestered in use for at least 100 years. This sequestration represents approximately one-half of the U.S. forest product industry's direct emissions, estimated by the U.S. Department of Energy to be approximately 22 million metric tonnes of carbon in 1994 [17]. The carbon sequestered in forest products during use clearly represents an important part of the forest product industry's carbon balance.

The estimate of net carbon sequestration developed using the 100-year method (12 million metric tonnes of carbon) is close to the estimate of 14 million tonnes of carbon developed for 1998 by the U.S. government using the national inventory method [19]. Although the two estimates are in reasonable agreement, it must be noted that they are estimates of two different quantities. The national inventory method estimates the *actual change in current stocks of carbon in products-in-use* whereas the 100-year method estimates *the long-term additions to stocks of carbon in products-in-use attributable to newly manufactured products*.[7]

6.0 Summary

Carbon sequestered in forest products represents an important part of the carbon profile of the forest products industry. Attempts are being made to account for this sequestration so that it can be included in corporate, sector, and value chain carbon balances.

National accounting methods are not suited for corporate accounting because they require data that are usually unavailable at the sub-national level. In addition, national inventory methods yield results that are heavily influenced by past production levels and historical product use patterns, making it difficult to use the results to characterize current performance. Finally, because national inventory methods are

[7] A less important difference that is specific to the estimates shown here is that the U.S. inventory estimate is based on domestic production while the 100-year method estimate is based on domestic consumption. The 100- year method can be used, however, to develop production- or consumption-based estimates.

focused on current and past conditions, they are not particularly useful for examining opportunities for future improvement.

An alternative method described in this paper, the 100-year method, is available for corporate, sector, and value chain carbon balances where it is important to characterize carbon sequestration in products-in-use. The method uses information on the expected time-in-use of products to estimate the amount of carbon therein that will still be sequestered in products-in-use in 100 years. The method uses readily available data, is simple and transparent, and can be used to characterize current performance and examine improvement opportunities.

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Figure 1. Decay curves for a 50-year half-life product

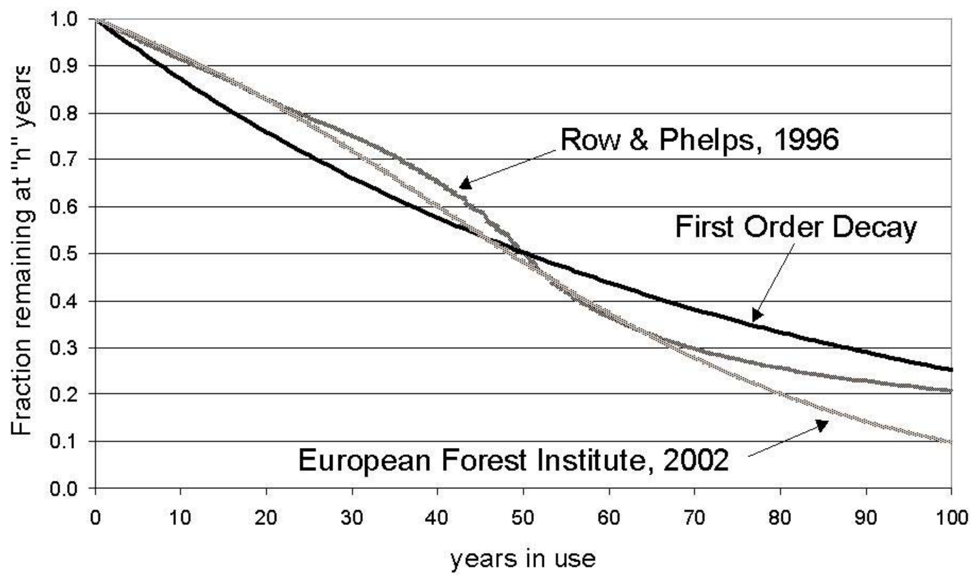

Figure 2. Fraction remaining at 100-years as a function of product half-life

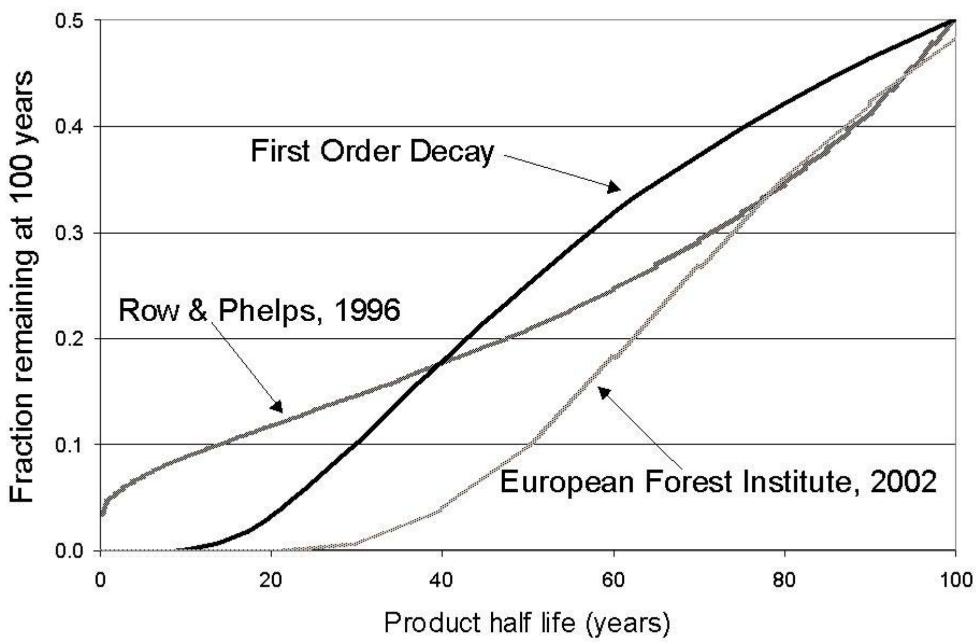

Table 1. Duration of carbon sequestration in end uses of wood and paper (Skog and Nicholson 1998) [26]

	Half-life of carbon (years)
Single-family homes (pre-1980)	80
Single-family homes (post-1980)	100
Multifamily homes	70
Mobile homes	20
Nonresidential construction	67
Pallets	6
Manufacturing	12
Furniture	30
Railroad ties	30
Paper (free sheet)	6
Paper (all others)	1

Table 2. Carbon sequestration in wood products in 1998

		single family residential	multifamily residential	mobile homes	residential upkeep	Non-residential construction	railroad ties	manufacturing - furniture	manufacturing - other	pallets and shipping	Other	
Consumption data for wood products from Reference 27												
Lumber	million bd. ft.	18352	1712	2100	14108	4617	700	5222	3155	7235	6874	
Structural panels	million sq. ft.	16282	1425	1688	7269	2879		1872	1862	622	890	
Nonstructural panels	million sq. ft.	3166	454	909	2710	1285		8634	2291	127	3385	
Conversion of wood product consumption data into carbon and sequestration estimates												
Total carbon in wood products	million metric tonnes carbon	15.04	1.40	1.77	9.93	3.48	0.35	4.83	2.61	3.86	4.37	
Fraction Remaining after 100 years	Fraction	0.346	0.292	0.119	0.119	0.278	0.147	0.147	0.095	0.075	0.072	TOTAL
Metric Tonnes Carbon Remaining after 100 years	million metric tonnes carbon	5.20	0.41	0.21	1.18	0.97	0.05	0.71	0.25	0.29	0.31	9.6

Notes:

Conversion from production statistics to tonnes of production based on conversion factors in Reference 28 and production statistics in Reference 27 (which were used to develop production-weighted conversion factors)

All products assumed to contain 50% carbon

Row and Phelps decay curves used to estimate fraction of carbon remaining in use after 100 years [24].

Table 3. Carbon sequestration in paper and paperboard products in 1998

1998 Paper and Paperboard Consumption [27]	101.1 million short tons
Carbon contained in 1998 consumption	46 million metric tonnes
Assumed half-life	1 year
Fraction remaining after 100 years	0.049
Tonnes carbon remaining in use after 100 years	2.25 million metric tonnes
Notes: All products assumed to contain 50% carbon Row and Phelps decay curves used to estimate fraction of carbon remaining in use after 100 years [24].	